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Wood waste as an alternative thermal insulation building material solution

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Wood waste as an alternative thermal insulation building material solution

Abstract

Current insulation materials in the construction market, which are predominantly inorganic materials, have a high performance in relation to heat transfer, i.e. high R-values, but the environmental impacts in their production processes are significant. The use of bio-based natural fibre materials such as cork, cotton, wood fibre, hemp, etc. with their lower embodied energy, moisture buffering capacity and, consequently, improved Indoor Environmental Quality have received increasing focus in both research and application, particularly amongst environmentally-conscious clients and designers.

In this study a natural fibre material in the form of wood waste is examined experimentally to assess its suitability for use as a thermal insulation material, without the addition of any binder, within a timber frame wall construction. The wood waste is from primary production sources using untreated material. According to our experimental results, the thermal conductivity values of wood waste with different densities, ranged from 0.048 to 0.055 W/mK. These values are slightly higher than commonly used inorganic based insulation materials, although comparable to other natural insulation materials in the market, but have the economic advantage of being a low-cost by-product. The values relating to the material hygric performance including the water vapour diffusion resistance factor, water vapour permeability, and water absorption coefficient were also determined and presented, which will help facilitate future hygrothermal modelling.

Keywords

Wood waste, Thermal Insulation, Natural Building Materials, Hygrothermal.

1. Introduction

Buildings and the construction industry are major contributors to global CO₂ emissions through embodied and operational energy use. The industry is a major consumer of natural resources and many products contain materials that are detrimental to the indoor environment and human health (Pacheco-Torgal *et al.*, 2012). One of the most effective measures to reduce operational energy use is to insulate the building envelope, which confers benefits in both heating and cooling energy use. Current thermal insulation materials in the construction market are generally inorganic materials e.g. extruded polystyrene (XPS), expanded polystyrene (EPS), polyisocyanurate and polyurethane foam. These materials have a high performance in resisting heat transfer but the environmental impact of their production processes is high. Accordingly, the use of natural materials, which undergo minimal production processing, for application as building insulation is an important aspect in the creation of a healthy and sustainable environment.

66 Recently, many studies have been conducted into the use of bio-based/natural fibre insulation materials as a
67 replacement for inorganic materials. Bio-based, i.e. plant- or animal-based, insulation materials are a novel class of
68 insulation materials which include products such as cork, cotton, wood fibre, flax, hemp, coconut, cellulose, rice,
69 sheep's wool and others. The plant-based materials sequester atmospheric carbon dioxide through photosynthesis
70 and consequently their use in construction can reduce the net embodied carbon dioxide of a building (Lawrence *et al.*, 2013). When used appropriately, these materials can deliver thermal and acoustic insulation performance
71 comparable to other insulation materials, but with a lower, or potentially negative, carbon footprint and fewer health
72 issues during installation (Sutton *et al.*, 2011). Moreover, they have hygroscopic properties, which have positive
73 effects on building energy consumption (Osanyintola and Simonson, 2006), HVAC system energy consumption in
74 dwellings (Steeman *et al.*, 2009; Woloszyn *et al.*, 2009) and indoor air quality in buildings (Simonson *et al.*, 2002).
75 Hygroscopic materials exposed to room air equilibrate indoor humidity through their ability to absorb, store, and
76 release water vapour from the air (Korjenic *et al.*, 2010; Simonson *et al.*, 2004; Shea *et al.*, 2012). This property
77 favourably influences the indoor air humidity, primarily in winter when prolonged periods of low indoor air humidity
78 may be experienced (Korjenic *et al.*, 2011), and reduces the potential for mould growth (Hall, 2010).
79
80 In the following studies, the use of natural fibre insulation materials without the addition of any binder is discussed
81 and their mechanical, thermal or hygrothermal characteristics are presented. Zhou *et al.* (2010) developed a
82 binderless cotton stalk fibreboard (BCSF) from cotton stalk fibres without resins and other chemical additives by hot-
83 pressing. The boards were produced at densities of 150–450 kg/m³ and achieved thermal conductivity values ranging
84 from 0.0585 to 0.0815 W/mK, which are close to those of expanded perlite and vermiculite within the same density
85 range. Korjenic *et al.* (2011) investigated the use of jute, flax, and hemp for use in the development of novel insulating
86 materials made from renewable resources and reported comparable thermal and mechanical properties to those of
87 established conventional insulation materials such as mineral wool, polystyrene and polyurethane. Panyakaew and
88 Fotios (2011) developed two low density thermal insulation boards, one made from coconut husk and another from
89 bagasse, both formed without the use of chemical binding additives. The results of their experimental study indicated
90 that both insulation boards had thermal conductivity values ranging from 0.046 to 0.068 W/Mk which, at the lower
91 end, were close to those of conventional insulation materials such as mineral wool. Zach *et al.* (2012) conducted a
92 series of measurements to evaluate the thermal performance and application of sheep's wool insulation. Results
93 indicated that the sheep's wool had comparable thermal performance to mineral/rock wool. Furthermore, the ability
94 of sheep's wool to absorb moisture helped to prevent condensation, regulate humidity, and created a pleasant indoor
95 atmosphere. Briga-Sá *et al.* (2013) experimentally studied the potential applicability of woven fabric waste (WFW)
96 and a waste of this residue, named woven fabric sub-waste (WFS), as thermal insulation for use in construction. The
97 results showed that the WFW had better insulation characteristics than the WFS, and the thermal conductivity value
98 of WFW was similar to the conventional thermal insulation materials, such as expanded polystyrene, extruded

99 polystyrene and mineral wool. Charca *et al.* (2015) studied the thermal properties of Ichu, which is an Andean feather
100 grass, as a local and cheap natural insulation material for rural dwellings. The results revealed that the thermal
101 conductivity varied from 0.047 to 0.113 W/mK for mats with unidirectional oriented fibres. Wei *et al.* (2015)
102 investigated the effect of high frequency heating, board density, particle size and ambient temperature on the
103 properties of a new thermal insulation material made from rice straw. The results indicated that the optimum physical
104 and mechanical properties of the boards were obtained with a moisture content of 14% and board density of 250
105 kg/m³. Additionally, the thermal insulation boards had good thermal performance, recording a thermal conductivity in
106 the range of 0.051 to 0.053 W/mK.

107 These studies highlight that natural building materials are increasingly being investigated as viable thermal insulation
108 materials for the external envelope of new and existing buildings. The highlighted studies focused primarily on thermal
109 and mechanical properties of these materials; few of them considered their hygric behaviour.

110 In this paper, the use of Wood Waste (WW) as an insulation material for building envelopes is investigated and
111 characterisation of its thermal and hygric performance is reported. WW is a common by-product of construction and
112 demolition, packaging, municipal activities, joinery and furniture manufacture (DEFRA, 2013). The use of this material
113 within timber frame wall construction, without the addition of binder, facilitates improved management of wood waste,
114 ease of recycling, and potentially healthier indoor environments. At the present time, wood fibers are used in the
115 production of wood fibre insulation boards by adding low quantities of PUR resin in a dry process. In this case, the
116 thermal conductivity values of the boards range between 0.037-0.05 W/mK (GUTEX,2015); however, this production
117 process also requires a large amount of energy (HPBP, 2017). The use of wood waste received from local sawmills
118 without treating will reduce energy use and relatedly carbon dioxide release.

119 Wood waste can be defined as a material that has been used for some time and then disposed by the users as well
120 as the residues from primary wood processing such as sawdust (Alf-Cemind, 2017). In this study, the properties of
121 the wood waste from primary production sources using untreated material are examined. These residues are
122 industrial wastes generated by either sawmills and other millwork companies, which are primary wood product
123 manufacturers, or companies that use products from wood materials milled by primary wood, which are secondary
124 wood product manufacturers. The primary wood manufacturers produce a variety of WW including bark, chips,
125 edgings, sawdust, and slabs. These residues typically have a moisture content of 40 to 50 percent. The secondary
126 wood product industries produce a variety of WW including chips, ends, and sawdust. The moisture content of these
127 wastes varies considerably because both green, harvested wood and kiln-dried wood are used in secondary
128 manufacturing. An average moisture content of 45 percent is commonly used in the wood energy industry (EPA,
129 1996).

130 Our paper reports the characterisation of the aforementioned WW from experimental testing of samples under a
131 range of environmental conditions as this is necessary to assess the performance of a thermal insulation material
132 used in the building envelope.

133 **2. Hygrothermal Behaviour**

134 The assessment of building envelopes subject to temperature and moisture gradients is a prerequisite in the
135 investigation of building energy efficiency and the evaluation and creation of a comfortable indoor environment (Moon
136 *et al.*, 2014). If such environmental conditions are not assessed with a holistic approach and appropriate solutions
137 integrated into the building design, the resulting building may suffer from excess energy use through increased heat
138 transmission coefficients of the building envelope elements. The building may also experience structural damage
139 from interstitial condensation and elevated moisture content, e.g. leading to timber decay, or surface condensation
140 damage in the form of mould which will lead to poor indoor air quality and an unhealthy environment. The building
141 element or zone response to temperature and moisture gradients is generally referred to as 'Hygrothermal behaviour'.
142 This behaviour considers the simultaneous and inter-dependent occurrence of heat absorption, storage, and release,
143 and moisture (liquid/vapour) absorption, storage and release (Hall, 2010). In air with a given relative humidity and
144 temperature, a porous building material, after some period of time exposed to such an environment, will reach a state
145 of equilibrium with this environment, exchanging the water in its pores with the ambient air. This relationship between
146 the water content and relative humidity is described by the sorption isotherm (Hansen, 1986). If the equilibrium is
147 achieved during drying, desorption isotherm is produced, and if achieved during wetting, the sorption isotherm is
148 realised (BS EN ISO 12571, 2013).

149 **3. Material**

150 The WW material used in the experiments was taken from a Welsh saw mill, and was the by-product of furniture and
151 joinery manufacturing. The material was used as received without addition of binders. The material particle size was
152 variable but within the range of approximately 1 - 4 mm and in a shape of long and thin curl (Fig.1).



153
154 Fig. 1. Wood waste as received from the saw mill (Source: Plant Fibre Technology ©)

155 WW can be applied to timber frame wall construction in the same way as the current application of cellulose fibres
156 (CF). CF can either be installed by 'loose fill' or 'wet spray method'. In the loose fill application, CF are first separated

157 by pneumatic equipment, and then are delivered by air pressure into wall cavities through a hose. In the wet spray
158 application, a separate pump is used to spray water and CF simultaneously in order to increase the adherence of the
159 fibres (Hurtado *et al.*, 2016). For both applications, when WW is used, it can slump under its own weight creating a
160 void at the top of the insulated space. The settlement serves to reduce the overall thermal resistance due to increased
161 heat transfer in the, relatively wide and un-filled, air void (Shea *et al.*, 2013). Generally, for all practical insulation
162 densities, thermal conductivity increases with increasing density and it is, therefore, important to place WW into the
163 wall construction at a density that balances adequate thermal resistance against ability to resist slump.

164 The hygroscopic nature of wood permits absorption and desorption of water vapour from the surrounding
165 environment, tending only to reach an equilibrium condition when the atmospheric relative humidity is stable. Under
166 varying environmental relative humidity conditions, typical of most occupied buildings, the moisture of wood is
167 changing continuously and an equilibrium is rarely reached (Popescu and Hill, 2013). Therefore, determining both
168 the thermal and hygroscopic properties of WW, as a wood residue, will be beneficial in order to facilitate dynamic
169 simulation of its performance and support design decisions for its use in timber frame wall construction as a thermal
170 insulation material.

171 **4. Experimental Methods**

172 The experiments conducted to determine the apparent (bulk) density, thermal conductivity, water vapour transmission
173 properties, true (absolute) density, water absorption coefficient and hygroscopic sorption/desorption properties of
174 WW are explained in the following sections along with a description of the test equipment, sample preparation, and
175 test procedures.

176 **4.1. Determination of Apparent (bulk) Density**

177 The apparent (bulk) density of WW was determined in accordance with BS EN 1602 which specifies the equipment
178 and procedures for determining the apparent density under reference conditions (BSI, 2013a).

179 **Preparing Samples and Test Procedures**

180 Three simple timber frames with the dimension of 400 x 400 mm were constructed and a 400 x 400 OSB sheet with
181 a thickness of 9 mm was fixed to the frame to form a rigid base to contain the WW material for laboratory testing.
182 The depths of the frames were 60, 50 and 40 mm in order to produce the samples with different densities, but equal
183 masses. These depths of containers were selected to suit the value required in the standard for testing loose-fill
184 materials (BSI, 2001a; ISO 8301), which must be at least 10 times the mean dimension of the beads, grains, flakes,
185 etc. of the loose-fill material.

186 The WW material was first dried in the oven at 50°C until its mass became constant. The mass was accepted to
187 become constant when the change of mass between three consecutive weighings became less than 0,1 % of the
188 total mass according to BS EN ISO 12571 (BSI, 2013c). The oven temperature was lower than prescribed in BS EN
189 ISO 12570 (BSI, 2013) but was chosen to limit surface scorching of low density WW, which was experienced at

190 higher temperatures. Accordingly, whilst stable mass was attained for all samples it is likely that some moisture may
 191 remain in the material. When the material had attained a constant mass, generally after around 48 hours, the samples
 192 were removed from the oven and placed into a conditioning room at controlled conditions of $23\pm3^{\circ}\text{C}$ and relative
 193 humidity of $50\pm5\%$. The time required for the conditioning of the wood waste was between 20 and 25 days. Fig. 2
 194 presents the drying and conditioning facilities used for the WW material.



200 Fig. 2. a) Drying WW, b) Conditioning WW.

201 After conditioning, the WW material was placed into a wood frame with a depth of 60 mm to a density that it would
 202 not slump under its own weight; the resulting mass of this material was measured by an electronic balance with a
 203 maximum capacity of 32 kg and resolution of 1 g. As the material does not have a rigid form, its volume was taken
 204 to be equal to the internal volume of the frame. The apparent density of WW in the frame, ρ , in kg/m^3 , was then
 205 calculated using Equation 1.

$$\rho = m / V \quad \text{(Equation 1)}$$

207 where

208 m is the mass of the test specimen, in kg;

209 V is the volume of the test specimen, in m^3 .

210 The same mass of material as used in the 60 mm deep container was placed, under compression, into the other
 211 frames which had depths of 50 mm and 40 mm, and the density was then determined using the same approach.

212 4.2. Determination of Thermal Conductivity

213 The thermal conductivity of the WW material was determined in accordance with BS EN 12667 and ISO 8301. BS
 214 EN 12667 specifies principles and testing procedures for determining, by means of the guarded hot plate or heat flow
 215 meter methods, the thermal resistance of test specimens having a thermal resistance of not less than $0.5 \text{ m}^2\cdot\text{K/W}$
 216 (BSI, 2001a). ISO 8301 defines the use of the heat flow meter (HFM) method to measure the steady-state heat
 217 transfer through flat slab specimens and the calculation of the heat transfer properties of specimens (ISO, 1991).
 218 Two types of thermal test instruments, ISOMET 2114 (for small samples) and Lasercomp FOX 600 Heat Flow Meter
 219 (for larger sample sizes up to $600 \times 600 \text{ mm}$, but not less than $250 \text{ mm} \times 250 \text{ mm}$), were used for thermal conductivity
 220 testing.

221 The Applied Precision ISOMET 2114 is a portable hand-held measuring instrument for direct measurement of thermal
 222 transfer properties of a wide range of isotropic materials including cellular insulating materials, plastics, glasses and

minerals. It is equipped with two optional types of measurement probes: needle probes for soft materials and surface probes for hard materials. The instrument applies a dynamic measurement method, which results in a much reduced measurement time in comparison with steady state measurement methods. The ISOMET measures the quantities of thermal conductivity (W/mK), volumetric heat capacity ($\text{J/m}^3\text{K}$), thermal diffusivity (m^2/s), and temperature ($^{\circ}\text{C}$) (AP, 2011).

The Lasercomp FOX600 is a Heat Flow Meter (HFM) instrument. In a heat flow meter, a specimen is positioned between two temperature controlled plates. These plates establish a user-defined temperature difference across the sample (LaserComp, 2010). The sample thickness can be set to match the target thickness of compressible samples, or, in the case of our test, the actual sample dimension, as detected by four in-built optical encoders. The resulting heat flux from steady-state heat transfer through the specimen is measured by two proprietary thin film heat flux transducers covering a large area of upper and lower sample surfaces and the thermal conductivity determined by reference to a calibration standard.

Preparing Samples and Testing Procedure

The tests using the ISOMET 2114 were performed for three different densities determined in Section 4.1, and two different moisture states, namely, oven-dried and conditioned to 50% RH. The material was placed into a cylindrical plastic container (Fig. 3). A plastic plate with a hole in the middle was installed over the container, and then the container was completely sealed with an aluminium foil to limit interaction between room air and the contained material. The needle probe of the ISOMET was inserted into the material, and the thermal conductivity of the material was measured.

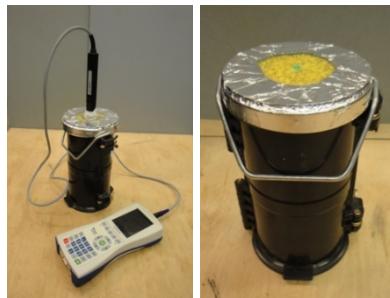
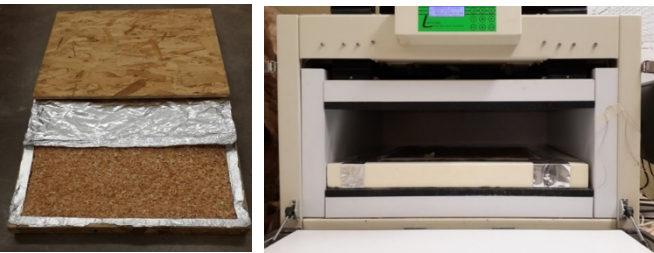


Fig. 3. Thermal conductivity testing using the ISOMET 2114 thermal analyser.

Heat Flow Meter thermal conductivity measurements

Prior to testing in the HFM, the wood frames and the WW were conditioned to the maintained condition of the University conditioning chamber, as described in Section 4.1. The weights of the WW material and the frames were measured throughout the conditioning process until they had achieved a constant mass, which was the state that the change of mass between three consecutive weighings, each made at least 24 h apart, became less than 0,1 % of the total mass. After drying, the interior surfaces of the frames were lined with an aluminium foil to limit exchange of moisture between the test material and the frame or external environment, which could affect the thermal measurements of the WW material. Finally, equal amounts of WW were placed into the wood frames and covered

251 with an OSB sheet and sealed (Fig. 4a). These samples, prior to being placed into the HFM instrument, were
252 surrounded by a thermal insulation board, which was made from polyisocyanurate ($\lambda = 0.022 \text{ W/mK}$), to further limit
253 edge heat losses (Fig. 4b).



254 (a) (b)
255 Fig. 4. a) WW and foil-lined OSB frame, b) WW and insulation in the HFM instrument.

256 The WW placed into the frame with the greatest volume (depth equal to 60 mm) was achieved through simple light
257 compression by hand. However, the same amount of material placed into the frame with the thickness of 50 mm
258 required compression from a series of G-clamps (Fig. 5a); and for the smallest volume frame (depth equal to 40 mm)
259 a press was used to apply a pressure of 25 kN (Fig. 5b).



260 (a) (b)
261 Fig. 5. a) The compression of wood frames by G-clamps, b) heavy-duty press machine.

262 Since the apparent (i.e. measured) thermal conductivity of materials will change depending on their temperatures as
263 well as their densities and moisture contents, the samples were tested at different temperatures as presented in
264 Table 1.

265 In a HFM, a temperature gradient is established through closely-controlled heating or cooling of the two plates that
266 sandwich the test specimen. Within the range for which the HFM is calibrated (-15°C to 65°C) and depending on
267 external cooling capacity, the temperature of each plate and hence heat flow direction can be selected by the user.
268 In agreement with the recommendations of the relevant test standards, all tests were conducted with an upward heat
269 flow direction and thus the lower plate was hotter than the upper plate. These tests, similar to the tests performed by
270 ISOMET, were carried out for two different moisture states, namely, oven-dried and conditioned to 50% RH.

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Table 1. HFM temperature set-points for all specimen samples.

Plate and mean temperatures (Samples 1, 2 and 3)		
T _{upper plate} (°C)	T _{mean} (°C)	T _{lower plate} (°C)
10	20	30
20	30	40
30	40	50

The raw HFM test results represent the total thermal resistance of both the frames and the WW material, i.e. the whole sample, including the OSB and timber frame. The thermal conductivity of the WW material alone was determined using Equation 2.

$$R_{\text{WHOLE SAMPLE}} = R_{\text{WOOD FRAME}} + R_{\text{WOOD WASTE}}$$

$$d_{\text{WS}}/\lambda_{\text{WS}} = d_{\text{WF}}/\lambda_{\text{WF}} + d_{\text{WW}}/\lambda_{\text{WW}} \tag{Equation 2}$$

where

- R : thermal resistance;
- d : thickness;
- _{WS} : the whole sample;
- _{WF} : the wood frame;
- _{WW} : the wood waste.

Equation 2 treats the sample as if formed of three, horizontal, homogeneous layers comprising OSB sheet, WW material, OSB sheet. The middle layer of the test sample clearly comprises both a perimeter wood frame and a thin vertical OSB edge, however, non-planar heat transfer is assumed to be negligible and is ignored as the area over which HFM measurements are recorded (a central thermopile core of approx. 254 mm x 254 mm) is much smaller than the area of the test specimen (400 mm x 400 mm), which is further surrounded by rigid insulation as indicated in Fig. 4b.

4.3. Determination of Hygroscopic Sorption/Desorption Properties

The hygroscopic sorption/desorption properties of the wood waste material were determined in accordance with BS EN ISO 12571 (BSI, 2013) using the desiccator method with suitable salt solutions to attain the desired range of relative humidity.

Preparing Samples and Testing Procedure

Three samples with the dimensions of 100 mm x100 mm were prepared. The samples of oven-dried WW were contained in a plastic mesh to achieve a density of 117 kg/m³ (Fig. 6a). The open mesh of the container allowed the WW to exchange moisture with the conditioned air in the desiccator chamber until equilibrium with the environment was attained. Table 2 presents the relative humidity values selected for measuring sorption/desorption at the air temperature of 23°C and the required salt solutions.

Table 2. Relative humidity and salt solutions.

No	Salt	Relative Humidity (%)
1	MgCl ₂ .6H ₂ O	33
2	Mg(NO ₃) ₂ .6H ₂ O	53
3	NaCl	75
4	KNO ₃	93

The sorption test was initiated with the solution prepared by mixing MgCl₂.6.H₂O and distilled water. This solution was put into a glass plate first, and then this plate was placed to the container to maintain the required relative humidity. A metal mesh was installed at 5 cm above the plate to raise the samples above the fluid level. A thin watertight, but vapour permeable, insulation layer was placed on the mesh to protect the samples from the solution. Prior to placing the samples in the desiccator, the mass of each sample was measured. After placing the samples, all joints between the container and its cover were sealed with an aluminium tape (Fig. 6b). Finally, the entire container was placed in a conditioning room which maintained an air temperature of (23±0.5)°C and a relative humidity of (50±5)%. The mass of the samples was periodically measured until they were in equilibrium with the environment (constant mass), which was the state that the change of mass between three consecutive weighings became less than 0,1 % of the total mass. When the aluminium tape was opened to measure the weight of the samples during the test, the relative humidity and the temperature inside the container were also checked with a humidity- temperature meter. This checking procedure can be seen in Fig. 6c. The measurements showed that the salt solutions provided the target conditions. After reaching the equilibrium, the test was repeated with Mg(NO₃)₂.6H₂O, NaCl, and KNO₃ respectively.

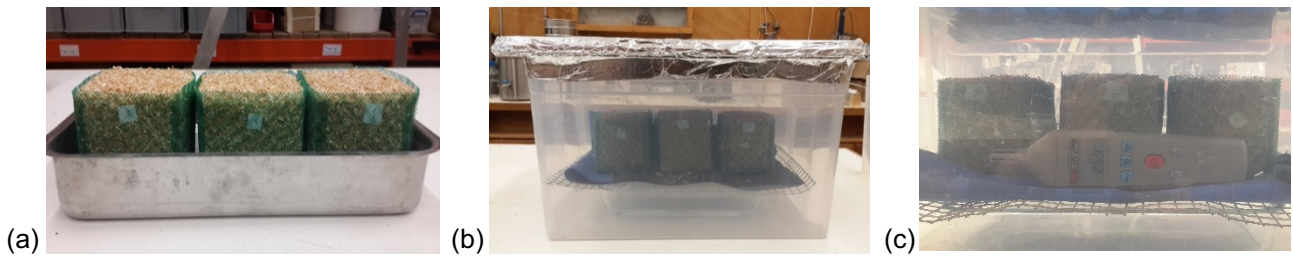


Fig. 6. a) The samples, b) The test set-up for desiccator method, c) The humidity / temperature meter inside the container.

The desorption test began with the solution of KNO₃ and distilled water, and the test was then repeated with NaCl, Mg(NO₃)₂.6H₂O, and MgCl₂.6.H₂O respectively.

4.4. Determination of Water Vapour Transmission Properties

The water vapour transmission properties of WW were determined in accordance with BS EN ISO 12572 which specifies a method based on cup tests for determining the water vapour permeance of building products and the water vapour permeability of building materials under isothermal conditions (BSI, 2001b).

334 Preparing Samples and Testing Procedure

335 Tests were conducted for both 'dry and wet cup' states, which provided information about the performance of the
336 WW material under low and high humidity conditions respectively. The accepted test conditions according to BS EN
337 ISO 12572 are presented in Table 3.

338 Table 3. Water vapour transmission test conditions.

Set	Condition (°C - RH%)	Tolerances		
		Temperature (°C)	Relative humidity (RH, %)	
			Set point	Tolerance
Dry State	23 - 50	23 ± 0,5	0	+3
Wet State	23 - 50	23 ± 0,5	93	±3

339
340 Three plastic containers with length and width each of 150 mm and a height of 80 mm were cut, leaving the upper
341 and bottom surfaces open. The bottom surfaces of these containers were covered with a plastic mesh, and filled with
342 the conditioned WW, to a density of 117 kg/m³. Every sample was then placed over the mouth of a test cup having
343 approximately the same size aperture as the plastic container, which included silica gel for the dry cup test. The joints
344 between the containers and the test cup were sealed with an aluminium tape. Finally, the test samples were placed
345 into the conditioning room. The weights of the samples were periodically measured to determine the rate of water
346 vapour transmission in the steady state; the containers remained sealed for the duration of the test. For the wet cup
347 test, the samples were prepared in the same manner as for the dry cup test but with Potassium nitrate (KNO₃) solution
348 to provide a relative humidity of 93% (Fig 7).



349
350 Fig. 7. The samples during the wet cup test.

351 4.5. Determination of True (Absolute) Density and Porosity

352 The true density of WW is determined by helium pycnometer, which gives the closest approximation to the true
353 density of a material. In this method, the helium penetrates the smallest pores, approaching the real volume (Donato
354 and Lazzara, 2012) and this value was then used to calculate the porosity value of WW.

355 An AccuPyc 1330 gas displacement pycnometer was used during the tests. In our tests, helium gas was used to
356 provide rapid and accurate results. The test procedure with regards to number of purges, purge fill pressure, number
357 of runs, and equilibration rate is presented in Table 4.

358

359

360

Table 4. The parameters for the true density tests

Parameters	Data
Number of purges	10
Purge fill pressure	19500 psig
Number of runs	10
Equilibration rate	0.0050 psi/min

361

362 The test set-up comprised of the pycnometer device and the cylinder containing helium as shown in Fig. 8.



363

Fig. 8. The test set-up for determining true density.

364

365 The porosity value of WW is calculated by Equation 3:

366

$$P = 100 \times (1 - (d_b / d_t)) \quad \text{(Equation 3)}$$

367 where

368 d_b : Bulk density

369 d_t : True density

370

371 Preparing Samples and Testing Procedure

372 The oven-dried WW was used for this test to prevent the distorting effect of water vapour on the volume measurement. An empty sample cup was first measured, and then the dried material was placed into the cup (Fig. 9). The amount of this material was calculated for the density of 117 kg/m³. The sample was then inserted into the cell chamber of the pycnometer device. After modifying the test parameters, the test was initiated. The value of the true density was obtained at the end of 10 purges and 10 runs. The test was repeated three times, and then the mean value of three measurements was calculated.

378

379



Fig. 9. a) The cup including WW b) The cup inserted into the cell chamber.

380 **4.6. Determination of Water Absorption Coefficient**

381 The water absorption coefficient of WW was determined in accordance with BS EN ISO 15148 which specifies a
382 method for determining, by partial immersion with no temperature gradient, the short-term liquid water absorption
383 coefficient (BSI, 2002). Since there is no other standard for loose materials, this method was applied for determining
384 the water absorption coefficient of WW.

385 **Preparing Samples and Testing Procedure**

386 The test conditions given in Table 5 were adjusted in accordance with BS EN ISO 15148.

387 Table 5. The water absorption test conditions.

388

Temperature (°C)	Relative humidity (%)
20 - 26	40 - 60

389 In accordance with the standard, and because of the difficulty in sealing a low density loose fill material, the WW was
390 placed into a tightly-fitting tube supported on a wire mesh placed over the mouth of the tube. In this test, six plastic
391 tubes with a diameter of 100 mm and a length of 80 mm were cut from a plastic pipe. The bottom surfaces of these
392 tubes were covered with a plastic mesh with very small holes (approximately 2 mm in diameter) that prevented the
393 particles from falling into the water. The containers were filled with the conditioned WW, to a density of 117 kg/m³. A
394 metal grid was then placed into a larger plastic container filled with water. This grid allowed the bases of the samples
395 remain clear of the bottom of the container. The level of the water in the container was controlled during the test to
396 ensure that it remained at 5 mm (± 2 mm) above the bases of the samples. Finally, six samples were placed over the
397 grid, and a timer was used to record the partial immersion time. After approximately 5 minutes the samples were
398 removed from the water, the surfaces were blotted with a damp sponge, and weighed. This procedure including
399 immersion, removal, surface drying and weighing was repeated at durations of 20 min, 1 h, 2 h, 4 h, 8 h, 12 h, 21 h
400 and 24 h to provide a series of masses m_t at times t . The procedures of blotting and weighing were carried out within
401 a minute and then the samples were returned to the water immediately afterwards. Fig. 10 presents the test set-up
402 including the container, grid, samples, scale, timers and sponge.



404 Fig. 10. The test set-up for the water absorption test.

405 This test was repeated for the WW sample with a density of 158 kg/m³ in order to examine the effect of density on
406 the water absorption of WW.

5. Experimental Results and Discussions

The results of the experiments carried out for determining apparent density, thermal conductivity, hygroscopic sorption/desorption curves, water vapour diffusion resistance factor, true density and water absorption coefficient are presented in this section.

5.1. Apparent Density

The apparent densities of three samples prepared with the conditioned WW were calculated using Equation 1, as described in Section 4.1. The first one, 117 kg/m³, is the density at which the WW would resist slump under its own weight. The others, 158 kg/m³ and 167 kg/m³, are the resultant values after compression in to shallower containers. All results are presented in Table 6. As required and expected, the density of WW increased as the thickness of the frame decreased since the cavities in the frame reduced due to the increased compression of the (same mass of) material.

Table 6. The apparent densities of WW in the different wood frames.

Samples	Density (ρ - kg/m ³)
Sample 1 (d= 60mm)	117
Sample 2 (d= 50mm)	158
Sample 3 (d= 40mm)	167
d : thickness of the sample	

5.2. Thermal Conductivity

The thermal properties i.e. thermal conductivity, volumetric heat capacity, and thermal diffusivity, measured by the ISOMET dynamic thermal analyser for different densities are given in Table 7. The results are presented for both the oven-dried WW and the conditioned WW.

Table 7. The thermal properties measured for the different densities of WW by ISOMET.

MATERIAL	Density (ρ - kg/m ³)	Thermal Conductivity (λ - W/mK)	Volumetric Heat Capacity (VHC - 10 ⁶ J/m ³ K)	Thermal Diffusivity (α - 10 ⁻⁶ m ² /s)
Oven-Dried Material	117	0.0528	0.1026	0.5153
	158	0.0554	0.1830	0.3080
	167	0.0558	0.1760	0.3168
Conditioned Material	117	0.0568	0.1546	0.3674
	158	0.0622	0.2249	0.2765
	167	0.0629	0.2133	0.2951

Fig. 11 presents the thermal conductivity values of WW measured by both the ISOMET device and the Heat Flow Meter. The HFM results are presented for the case of a 20°C temperature difference between measurement plates

428 and a mean temperature of 30°C. The values measured by HFM were consistently lower than the values measured
 429 by the ISOMET unit. The ISOMET applies a dynamic heat flux measurement method, which enables it to reduce the
 430 measurement time in comparison with steady state measurement methods. The HFM use a steady-state heat flux
 431 measurement method as explained in Section 4.2. The stated accuracy of the two devices is 1% for the Heat Flow
 432 Meter (LaserComp, 2010) and 5% of reading+0.001 W/mK for the ISOMET device (AP, 2011). The results taken
 433 from both instruments, as expected, indicated that the increased moisture content due to conditioning of the material
 434 caused the thermal conductivity to increase.
 435 Whilst the expected general trend of increasing apparent thermal conductivity with increasing density, increasing
 436 moisture content, and increasing temperature is apparent (Figures 11 and 13), it is evident that, accepting the
 437 different degree of error between the HFM and ISOMET devices, there is a consistently higher value of thermal
 438 conductivity reported by the ISOMET device (Figure 11) relative to the HFM; the difference between the apparent
 439 thermal conductivity being greatest for the conditioned samples. The transient measurement method employed by
 440 the ISOMET needle probe, a variation of the Hot Wire method, has some advantages relative to the Heat Flow Meter
 441 e.g. reduced sample material quantity, small temperature gradient, and short test duration. However, other
 442 investigators (Campanale and Moro, 2016) have identified that the heating sensor causes a latent heat exchange
 443 due to the phase changes in the water inside the specimen close to the sensor, and this influences the thermal
 444 conductivity measured value. Whilst the Heat Flow Meter causes moisture migration between hot and cold plates it
 445 has been demonstrated (Deganello et al., 2013, cited in Campanale and Moro, 2016) that for specimens with a
 446 moisture content lower than 8.5% the error due to phase changes and moisture redistribution is less than 2.5% if the
 447 thermal conductivity is derived from the HFM measurements recorded after reaching steady state, which is the case
 448 for our presented results.

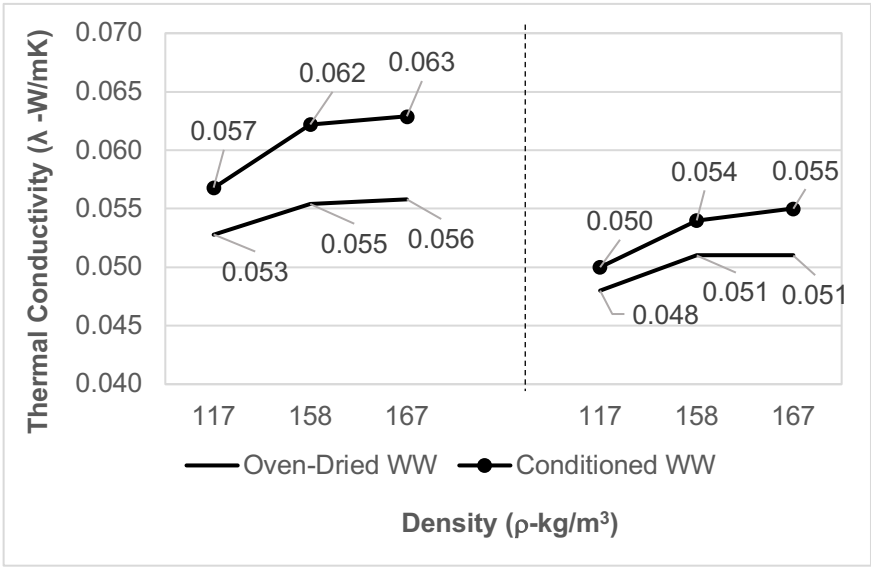
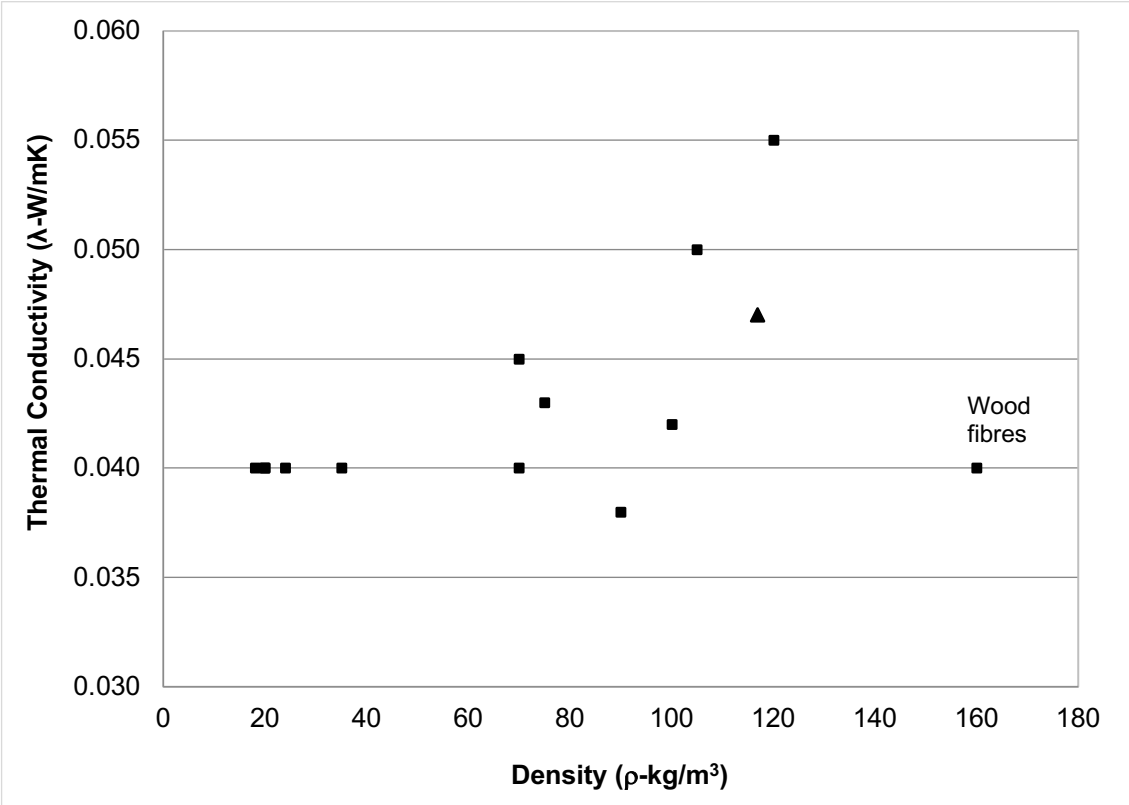


Fig. 11. The thermal conductivity values for different densities of WW by HFM and ISOMET.

452 In addition to variations due to moisture, density and temperature, there are numerous other factors that could
453 influence the measured thermal conductivity in both test methods including, for example, surface contact resistance,
454 inhomogeneity in the material sample, sample geometry, directional-dependencies (anisotropy) etc. For the oven
455 dried samples, the difference between HFM and the ISOMET device is +/-10%. Rides et al. (2009) performed inter-
456 comparison tests of a range of methods including both Hot Wire probes and Heat Flow Meters and observed
457 variations of 6% for thermal conductivity, albeit on a more homogeneous and isotropic plastic material.
458 The measured thermal conductivity of oven-dried value of WW (0.048 W/mK) with the density of 117 kg/m³ is similar
459 to that of the lower density wood chipping material reported in Gellert (2010); and better than cereal and reeds of
460 similar density (Fig. 12).



475 Fig. 12. Thermal conductivity versus density for different natural insulation materials

476
477 Fig.13 presents the temperature-dependent thermal conductivity, as measured using the HFM, of the oven-dried and
478 conditioned WW for all densities.

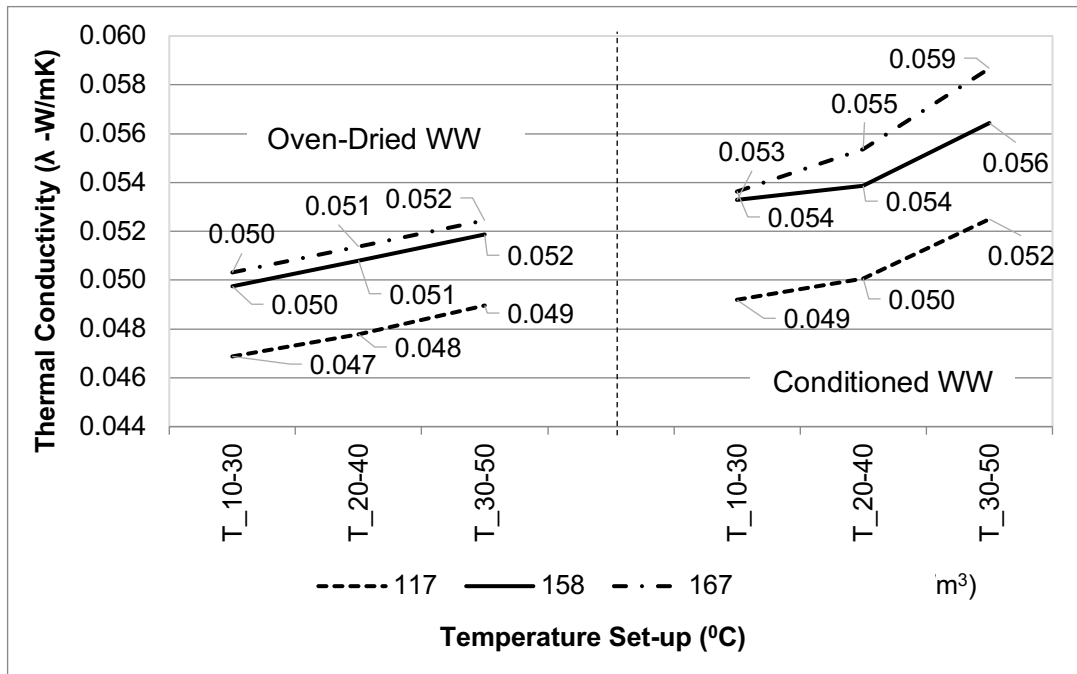


Fig. 13. Thermal conductivity values measured by HFM for WW.

As expected, the thermal conductivity of the material increased as the temperature increased for both the oven-dried and conditioned WW, and all densities. The thermal conductivity of the conditioned samples was higher due to their increased moisture contents. While the differences between the oven-dried and conditioned samples changed 7-11% when measured by ISOMET, they changed 4-7% when measured by HFM because of the different measurement methods of the devices as discussed in Section 5.2.

5.3. Determination of Hygroscopic Sorption/Desorption Properties

The moisture contents at each relative humidity were calculated using Equation 4 as presented in BS EN ISO 12571 (BSI, 2013). These values and their standard deviations for each relative humidity are given in Table 8. According to the results, the biggest difference in the moisture contents of the samples were calculated for 93% RH during the sorption.

$$u = (m - m_0) / m_0 \quad (\text{Equation 4})$$

where

m : the mass of the test specimen at each relative humidity.

m_0 : the initial mass of the test specimen

Table 8 The moisture contents at each relative humidity.

Samples	Moisture contents at sorption				Moisture contents at desorption			
	33%RH	53%RH	75%RH	93%RH	93%RH	75%RH	53%RH	33%RH
Sample 1	0,045	0,068	0,109	0,153	0,159	0,118	0,086	0,069
Sample 2	0,045	0,065	0,106	0,143	0,159	0,123	0,082	0,072
Sample 3	0,044	0,067	0,109	0,149	0,158	0,116	0,082	0,067
St Deviations	0,0005	0,0017	0,0019	0,0050	0,0005	0,0036	0,0023	0,0024

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The moisture contents of WW versus the relative humidities inside the plastic container during the test are given in Fig. 14. In common with isotherm test results for many other materials, hysteresis was observed in the material. The duration of the tests varied between 20 and 30 days depending on the target relative humidity. It took approximately one month for the high relative humidity values to be obtained. The moisture content of WW from 33%RH and 93%RH increased approximately 11% at sorption, and decreased approximately 9% during desorption across the same range. In addition, the moisture content increased more rapidly from 53%RH upwards.

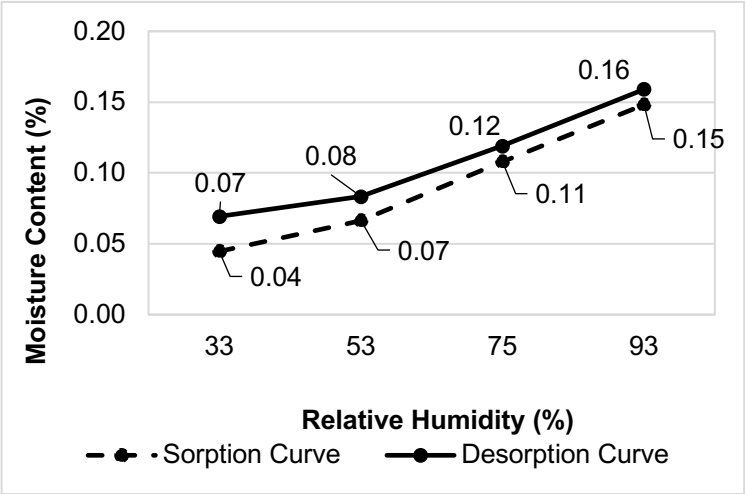


Fig. 14. Sorption and desorption curves for WW.

5.4. Determination of Water Vapour Transmission Properties

Table 9 presents the results of the dry and wet cup tests for WW calculated using Equations 5-10, and the standard deviation values calculated for three samples. As expected, these results indicate that WW has a low water vapour resistance at high relative humidity compared to the low relative humidity conditions. Moreover, the permeability of WW was higher at high relative humidity, i.e. the permeability of the material increased as the relative humidity increased.

Table 9. The results of the dry and wet-cup tests for WW.

Water Vapour Transmission Properties	Eq (5-10)	Dry Cup Test	Standard Deviation (three samples)	Wet Cup Test	Standard Deviation (three samples)
Water Vapour Permeability (δ) - (kg/msPa)	$\delta = W.d$ (Eq.5)	2.20E-11	4,27E-13	4.92E-11	1,07E-12
Water Vapour Diffusion Resistance Factor (μ) - (-)	$\mu = \delta_{air}/\delta$ (Eq.6)	9,06	1,76E-01	4,05	8,92E-02
Water Vapour Diffusion Equivalent Air Layer Thickness (s_d) - (m)	$s_d = \mu.d$ (Eq.7)	0.68	1,32E-02	0.30	6,69E-03
Water Vapour Transmission Rate (g) - (kg/m ² s)	$g = G/A$ (Eq.8)	4.19E-07	8,16E-09	9.39E-07	2,05E-08
Water Vapour Permeance (W) - (kg/m ² sPa)	$W = G/A \cdot \Delta p_v$ (Eq.9)	2.93E-10	5,70E-12	6.56E-10	1,43E-11
Water Vapour Resistance (Z) - (m ² sPa/kg)	$Z = 1/W$ (Eq.10)	3.42E+09	6,65E+07	1.53E+09	3,31E+07
<u>Other Abbreviations</u> d : Layer thickness s_d : Water Vapour Diffusion Equivalent Air Layer Thickness G : Water vapour flow rate through specimen Δp_v : Water vapour pressure difference across specimen A : Area of specimen Eq : Equation					

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523 The results of the dry and wet cup tests conducted by Vololonirina *et al.* (2014) for wood fibre (WF) material are
524 compared to our results for wood waste (WW) in Table 10.

525 Table 10. The results of the dry and wet-cup tests for WW and WF.

	Dry Cup Test		Wet Cup Test	
	WF	WW	WF	WW
Water Vapour Permeability (δ) - (kg/msPa)	3.60E-11	2.20E-11	8.30E-11	4.92E-11
Water Vapour Diffusion Resistance Factor (μ) - (-)	6	9.06	2	4.05

526

527 The cup tests demonstrate that WW has slightly increased resistance to water vapour diffusion relative to the WF
528 material; proportionally more so at the higher humidities of the Wet Cup test where the transport of liquid water
529 increases and vapour transport diminishes. Where transfer is dominated by vapour diffusion, WW records diffusion
530 resistance more than 50% higher than WF.

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532 **5.5. Determination of True (Absolute) Density and Porosity**

533 The true density values measured by the Pycnometer device and the porosity (P, %) values calculated by Equation
534 3 for the density of 117 kg/m³ of are presented in Table 11. Since the true density measurements repeated three
535 times gave similar results to each other without obtaining any extreme value, their means were given in the table.

536 Table 11. The measured true densities and the calculated porosity values for different densities.

Apparent (Bulk) Density (g/cm ³)	True (Absolute) Density (g/cm ³)	Porosity (%)
0.117	4.348*	97
* The mean value of three measurements.		

537

538 The porosity results revealed that WW is comparable to other natural fibre materials such as those recorded by
539 Palumbo *et al.* (2016) which included hemp fibre, wood wool and wood fibre which were 97%, 96% and 86%,
540 respectively.

541 **5.6. Determination of Water Absorption Coefficient**

542 The mean mass change of six samples, and for two densities, versus the square root of the weighing times, is
543 presented in Fig. 15. The difference between the mass at each weighing and the initial mass were divided by the
544 area of the open end of the sample (Equation 11), and plotted against the square root of the weighing times, \sqrt{t} .

545
$$\Delta m_t = (m_t - m_i) / A$$
 (Equation 11)

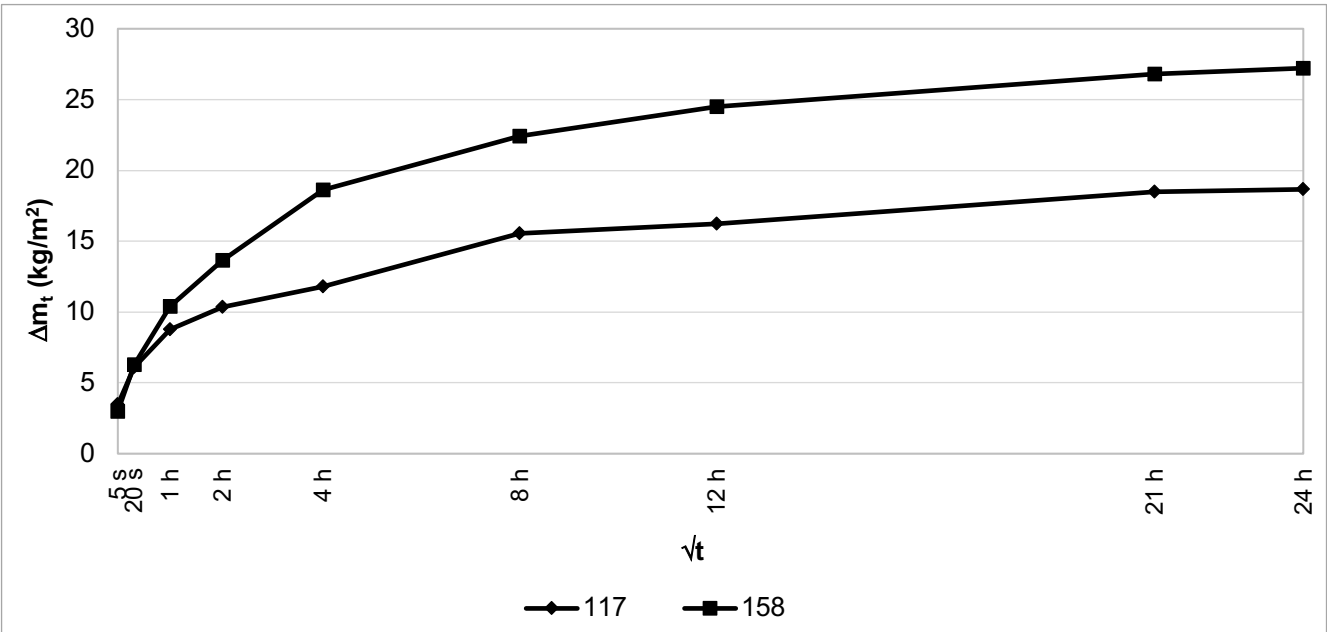
546 where

547 m_t mass of sample 24 h after the start of the test;

548 m_i initial mass of sample;

549 A area of open end of sample;

550 t time.



551

552 Fig. 15. The mass changes versus weighing times for two densities.

553 The water absorption coefficients for two densities were calculated according to BS EN ISO 15148 (BSI, 2002) by
 554 using Equation 12, and the results were given in Table 12.

555

$$A_{w24} = m_{tf} / \sqrt{t}$$

Equation (12)

556 where
 557 m_{tf} : the value of m 24 h after the start of the test
 558

559 Although limited to sample of just two different densities, the water absorption coefficient increases as the density
 560 increases. The samples with the density of 158 kg/m³ absorbed the water approximately 48% more than the ones
 561 with the density of 117 kg/m³ due to increasing the amount of particles.

562 Table 12. The water absorption coefficients for different densities

Density (ρ - kg/m ³)	Water absorption coefficient (A - kg/m ² s ^{0.5})
117	0,063
158	0,093

563
 564 According to Mukhopadhyaya *et al.* (2002) white pine wood, red clay brick and concrete have water absorption
 565 coefficients of 0.0112 kg/m²s^{0.5}, 0.084 kg/m²s^{0.5} and 0.184 kg/m²s^{0.5}, respectively, at a temperature of 21°C. When
 566 these values are compared to our results, it is seen that WW's water absorption coefficient is very close to red clay
 567 brick's.

568 **6. Conclusions**

569 Current insulation materials used in construction industry are generally inorganic based materials such as extruded
 570 polystyrene, expanded polystyrene, and polyurethane foam. Although these materials have a high performance with
 571 regards to the resistance to conduction heat transfer, their environmental impacts during the building life cycle period,
 572 and especially in the production process, are generally high. Therefore, the use of bio-based materials instead of
 573 inorganic based materials has become an important issue in terms of reducing environmental impacts and improving
 574 building whole life cycle performance primarily with regards to reduced embodied energy.

575 For this research, the characterisation of the hygrothermal properties of waste wood (WW) was undertaken with the
 576 aim to provide greater understanding of the material performance and its application as an insulation material in
 577 timber frame wall construction.

578 WW can be applied to timber frame wall construction by manual filling or mechanical blowing of the loose fill material
 579 between the studs of the frame and without any binder. The density of 117 kg/m³ was found to be a functional density
 580 level that can be achieved without mechanical compression and has thermal performance comparable to similar
 581 materials. However, its suitability at full-scale requires further investigation to ensure that the material does not slump
 582 under its own weight, which would lead to overall increased heat loss. According to the experimental results obtained

583 in this investigation, WW could be efficiently used as a thermal insulation material. Its measured thermal conductivity
584 value was close to the values of wood fibres, wood chippings and straw bale, and lower than reeds and cereal, which
585 have already been used as natural insulation materials in the construction market. When compared to inorganic
586 insulation materials, it has a higher thermal conductivity value. The moisture content at a range of relative humidities
587 during sorption and desorption testing was similar to reported values for wood fibre material. Additionally, we have
588 reported a range of hygric and thermal material properties at a range of densities, which can be used to facilitate
589 Hygrothermal analysis, e.g. through computer simulation with tools such as WUFI, which can in-turn provide valuable
590 supporting information for evaluation of low impact building designs employing this natural low cost and low impact
591 locally available material.

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